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Coplanar Waveguide Using Ferroelectric Thin Oxide Film: Dielectric *Constant*

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Abstract. Coplanar waveguide (CPW) transmission lines were fabricated on thin ferroelectric $Ba_{1-x}Sr_xTiO_3$ films for tunable microwave applications. The growth of the ferroelectric oxide films was accomplished by a pulsed laser deposition with a partial oxygen background. Microwave properties of the CPW phase shifter were measured using a HP 8510C vector network analyzer from 0.045–20 GHz with −40–40 V of dc bias. A large phase shift angle of ∼120° at 10 GHz was observed from the CPW (gap = 4 μm, length = 3 mm) with a 40 V of dc bias change. The dielectric constant of the thin ferroelectric film was extracted from the dimension of the CPW (gap, width, length) and the measured S-parameter by a modified conformal mapping. However, the dielectric constant of the ferroelectric thin film exhibits a gap dependency; dielectric constant (990–830) decreases with increasing gap size (4–19 μm, respectively). By adjusting the filling factors of the film, a 'constant' dielectric constant of BST film is found to be 810 ± 5.

Keywords: $(Ba,Sr)TiO_3$, thin film, ferroelectric, conformal mapping, phase shifter, microwave

1. Introduction

Ferroelectric thin films, which exhibit electric field dependent dielectric constant, are being used to develop a new class of tunable microwave devices [1–7]. An important tunable microwave device using ferroelectric film is a wideband phase shifter—an important component of the phased array antenna. A simple co-planar waveguide (CPW) type phase shifter has advantages over other type phase shifters; easy fabrication with one photomask, and easy to measure the microwave characteristics.

In order to extract the dielectric constant of the film, a modified conformal mapping method has been used. The modified conformal mapping developed from the dielectric thin films with relatively low dielectric constants (∼few tens). Since ferroelectric materials with a very large dielectric constants, such as 100–1000s, a deviation between extracted and real dielectric constants of ferroelectric thin films have been expected but no clear evidence has been reported yet.

In this paper, we report the microwave characteristics of the CPW fabricated on $(Ba_{0.6}Sr_{0.4})TiO_3$ (BST) in terms of differential phase shift and dielectric constant of BST. The fabricated CPW phase shifters exhibited a large differential phase angle with a dc bias field of less than 80 kV/cm between center and ground conductors.

At the end of this paper, we will discuss dielectric properties of the BST film in terms of the gap size of the device, which exhibits that the dielectric constant of the BST extracted by the conformal mapping increases with decreasing gap size. We introduced a simple empirical method to adjust dielectric constant of a thin layer of high-k material by the adjusted conformal mapping method. Extracting reasonable dielectric constant of a high-k thin film is essential for designing matched transmission lines especially in microwave region. Also this will give us an idea how

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the dielectric properties of ferroelectric films extracted from devices with different gap sizes reported in articles can be compared.

2. Film Growth and Device Fabrication

Single phase BST films were deposited using a well-known pulsed laser deposition (PLD) method onto (001) MgO single crystal. A focused Kr:F excimer pulsed laser was used to ablate BST target. MgO substrates were heated at 750°C and the deposition chamber was kept in the oxygen pressure of 170 mTorr. The thickness of the BST films were controlled by changing the deposition time, and confirmed from a cross-sectional view of the film by scanning electron microscopy. The structure of the films were routinely investigated by X-ray diffraction, and found be epitaxial film growths. A typical X-ray diffraction pattern of BST/MgO is shown in Fig. 1. The diffraction pattern exhibits (00*l*) related BST peaks, such as (001), (002), and (003), and (002) of MgO substrate peak. Peaks labeled as Au are corresponding to the Au metal layer used for electrodes of devices. A narrow full width half maximum of ~0.55° taken from the θ rocking curve of the (002) BST peak demonstrates a good crystalinity of the deposited BST film. A thick Au/Cr layer (2 μm) was deposited by sputtering method. Devices were fabricated on BST films through a conventional photo-lithography with a dry etching technique. Microwave properties of the CPW were measured at 0.1–20 GHz range by a HP 8510C network analyzer. Dielectric constants of the films were extracted using a modified conformal-mapping method from measured S-parameters and dimensions of devices.

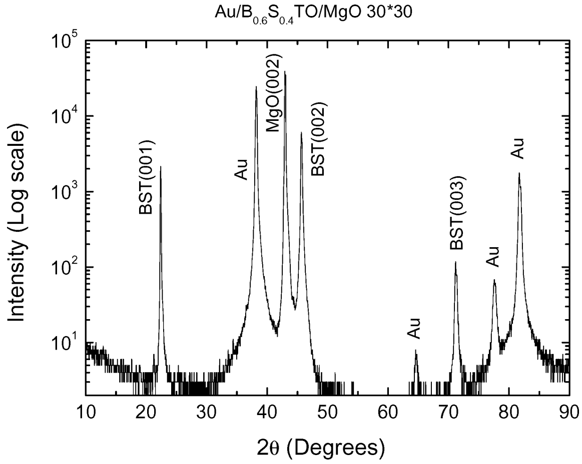


Fig. 1. X-ray diffraction pattern of Au/BST /MgO.

3. Gap Dependent Properties of Phase Shifters

It is difficult to extract a dielectric constant from a high dielectric thin layer. Though dielectric constants of BST films have been calculated using (modified) conformal mapping method, the validity of the model with extreme boundary conditions need further verifications with experimental results.

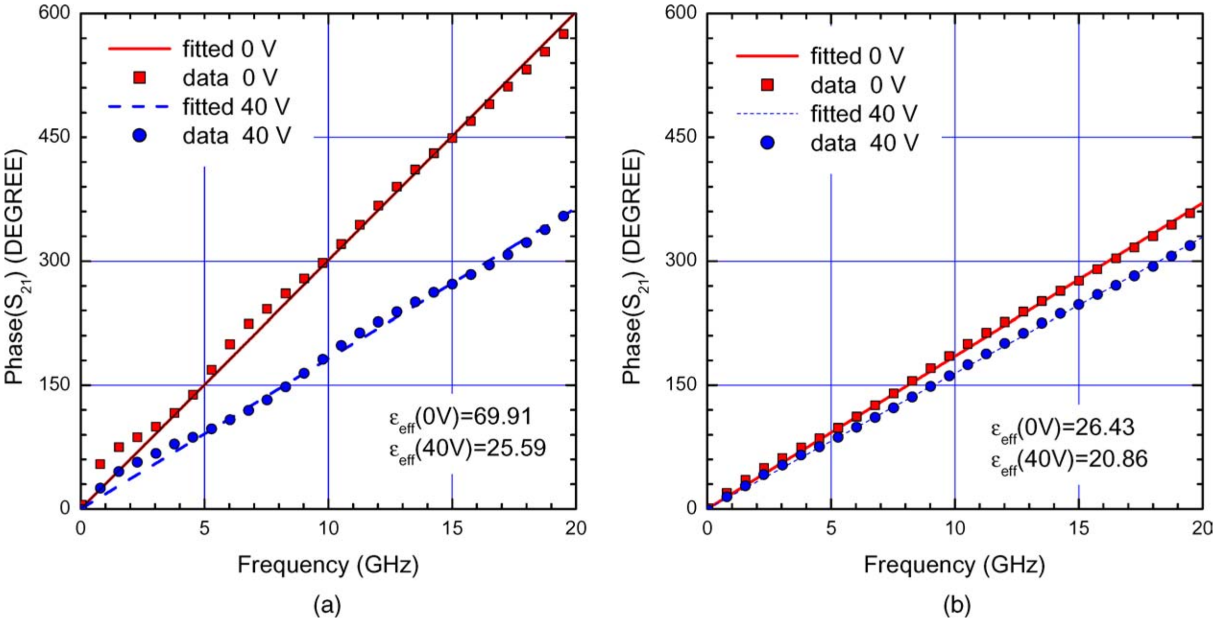
Figure 2 shows frequency dependent total phases of S_{21} at 0 and 40 V of applied dc bias voltages measured from two CPWs with gap size of 4 and 19 μm. Decreasing electrical length of device with increasing bias voltage is evident from Fig. 2, since dielectric constant of the ferroelectric films decreases with increased bias voltages. The measured phase shift angle of a 4 μm gap CPW with 0–40 V of bias voltage ranges 120–240° at 10–20 GHz, respectively. These values are significant since large differential phase shifts are achieved with such a low bias voltage of 40 V and a short length of 3 mm. Since differential phase shift angle with 40 V is not saturated yet, it will increase further with a higher dc bias voltage and expected to reach at least 180° at 10 GHz with 100 V.

Dielectric constant of the ferroelectric BST film is calculated from the total phase of S_{21}, which is equivalent with the electrical length. The electrical length of the device can be expressed as following,

$$\phi_{21} = 2 f_o \sqrt{\varepsilon_{\mathrm{eff}} \mu_{\mathrm{eff}}} \times l \times 180/c, \tag{1}$$

where f_o is the operating frequency, $\varepsilon_{\mathrm{eff}}$ and μ_{eff} are the effective dielectric constant and magnetic permeability of the device, respectively, l is the length of CPW, and c is the light velocity in the air. Figure 2 shows that the measured total phase ϕ_{21} of the CPW agrees well with those of fitted using Eq. (1) when $\mu_{\mathrm{eff}} = 1$. Minor deviations at low and high frequency ends are observed in the graph, which may attributed to the frequency dependent non-linear response of ferroelectrics. To extract the dielectric constant of ferroelectric film, a modified conformal mapping technique has been used. [8, 9]. Dielectric constant of substrate, film, and air have the following relation,

$$\varepsilon_{\mathrm{eff}} = k_{\mathrm{sub}} \varepsilon_{\mathrm{sub}} + k_{\mathrm{film}} \varepsilon_{\mathrm{film}} + k_{\mathrm{air}} \varepsilon_{\mathrm{air}}, \tag{2}$$



(a) (b)

Fig. 2. Total S_{21} phase of CPW with 3 mm in length, 21 μm in width, and (a) 4 μm and (b) 19 μm of gap sizes.

where k's are corresponding to the filling factors for the substrate, film and air. The calculated film dielectric constant of 4 μm gap CPW decreases from 990 at 0 V to 310 at 40 V. This is corresponding to ~70% of dielectric constant change with 80 kV/cm of a dc bias field, which is comparable with those of the reported BST films [1–7].

In order to extract dielectric constant of ferroelectric BST films, dimensions of the CPWs were measured by SEM. The dimensions of the devices found to be 1 μm larger in center conductor width and 1 μm narrower in gap size than the original mask dimension, which difference was caused by etching process. The final dimension of the CPW were gap size of 19, 14, 9, 6, and 4 μm, while the width of the center conductor was kept in 21 μm and the length of the device was fixed at 3 mm. The thickness of BST film used in this experiment is 630 nm measured by a cross-sectional SEM.

Then, the dielectric constant of the BST film was calculated from the effective dielectric constant based on the conformal mapping method (Eq. (2)), and the resulting dielectric constant of the film without bias field are shown in Fig. 3.

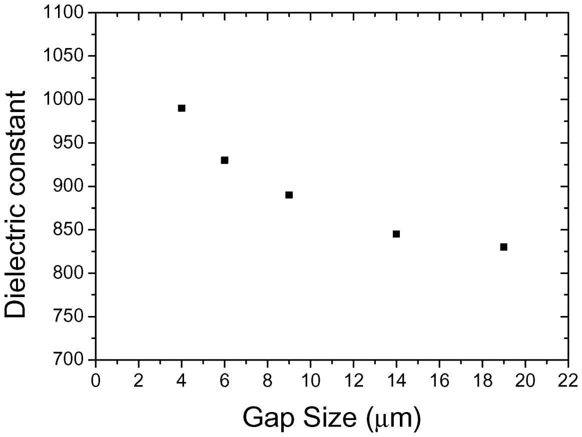


Fig. 3. Gap dependent dielectric constant of the high dielectric BST film without bias fields.

From the Fig. 3, one can find an interesting tendency that the calculated dielectric constant decreases with increasing gap size. This suggests that the conformal mapping and/or the nature of the ferroelectrics are not understood completely. Since we are dealing with high dielectric constant materials, the conformal mapping developed for low dielectric constant materials may cause some degree of deviation when the condition is extreme, such as high-k, thin-layer, and narrow gap, etc. The other possible origin of deviation may come from the anisotropic dielectric constant of ferroelectric films, since ferroelectric BST thin films grown on MgO exhibited distorted lattice constants along a

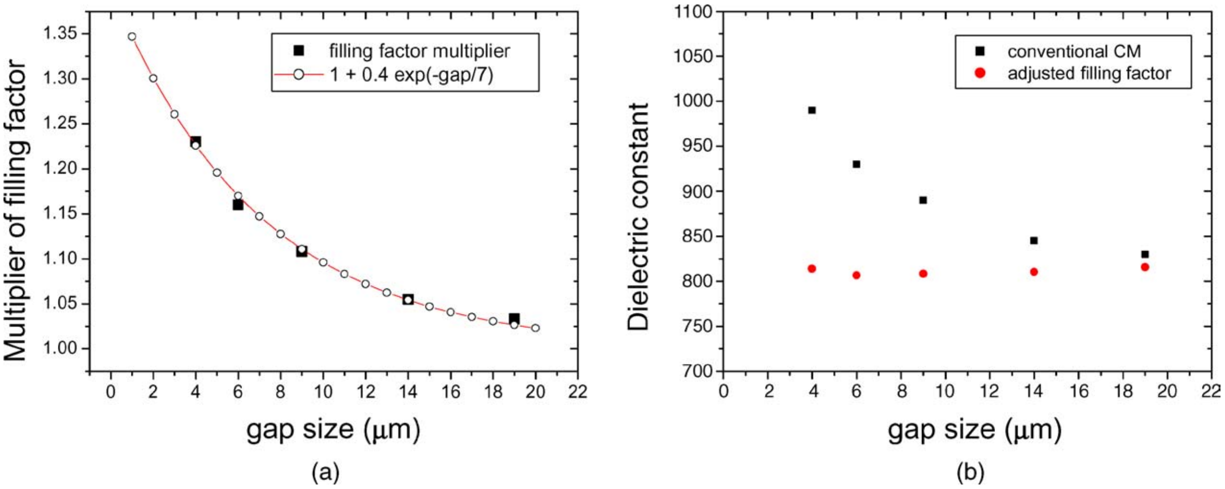


Fig. 4. (a) Multiplier factor and (b) dielectric constant after calculation using adjusted filling factors for the given gap dimensions.

and *c*-axis [1, 10, 11]. Anisotropic dielectric constant of distorted BST should investigated further to get clear understand.

Though the nature of the dielectric constant variation with gap size is unknown, we tried to find an empirical formula to get a 'constant' dielectric constant of the BST film to give an idea of physical properties of the film. The first step was changing filling factor of film, since there was a strong possibility of underestimation of the film filling factor hinted from the gap dependent dielectric constant calculated by a conventional conformal mapping.

To accept the change in filling factor of BST film need a few assumptions; the dielectric constant of the film without dc bias field is *unique* for the given film and *independent* from the gap dimension. The film filling factors at the given gap dimensions have been adjusted to get a 'constant' dielectric constant though different gap dimensions (4–19 μm). The filling factor of film (k_{film}) has been substituted by an adjusted filling factor defined by following equation,

$$\begin{aligned} k_{\text{film}}^{n} &= k_{\text{film}} \times M_{\text{gap}}, \\ M_{\text{gap}} &= 1 + 0.4\exp(-\text{gap}/7). \end{aligned} \tag{3}$$

Multiplier M_{gap} is shown in Fig. 4(a). By using adjusted filling factor, dielectric 'constant' of BST film with different gap sizes are shown in Fig. 4(b). The 'constant' dielectric constant of BST film is found to be 810 ± 5 without dc bias shown in Fig. 4(b). This method will give us a way of comparing dielectric constants films reported in articles.

4. Summary

CPW type phase shifters have been fabricated on BST/MgO using a 2 μm thick metal layer. The fabricated CPW phase shifter (21 μm in width, 4 μm in gap, and 3 mm in length) exhibited differential phase angles of 120–240° at 10–20 GHz with a dc bias voltage of 40 V between center and ground conductors. Gap size dependent dielectric constant of the BST film was observed, which was attributed to the imperfect of the conventional conformal mapping method. Since we are dealing with extreme conditions in terms of dielectric constant and film thickness, we need to adjust the filling factor of the films to get a dielectric 'constant'. The newly calculated dielectric 'constant' of the BST film was found to be 810 ± 5. However, more studies are necessary to understand the nature of the film to get a real 'constant' of the film, which may depend on the orientation of crystal structure. In addition to this, we clearly demonstrated that possible application of ferroelectric tunable devices on a microwave wireless telecommunication.

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